

Spintronic devices on the base of magnetic nanostructures

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Abstract

Two types of spintronic devices on the base of magnetic nanostructures containing silicon dioxide films with cobalt nanoparticles $\text{SiO}_2(\text{Co})$ on GaAs substrate – magnetic sensors and field-effect transistor governed by applied magnetic field – are studied. Magnetic sensors are based on the injection magnetoresistance effect. This effect manifests itself in avalanche suppression by the magnetic field in GaAs near the $\text{SiO}_2(\text{Co})/\text{GaAs}$ interface. Field-effect transistor contains the $\text{SiO}_2(\text{Co})$ film under gate. It is found that the magnetic field action leads to great changes in electron mobility in the channel due to the interaction between spins of Co nanoparticles and electron spins.

1 Introduction

Manipulation of carrier spins in ferromagnetic / semiconductor heterostructures offers enhanced functionality of spin-electronic devices such as spin transistors, sensors, and magnetic memory cells [1, 2]. This manipulation can be realized on the base of magnetic nanostructures by use of magnetoresistance effects and due to interactions between magnetic nanostructures and electron spins in field-effect transistors. Magnetoresistance effects are attracting much attention in a view of their various applications. An extremely large magnetoresistance (10^5 %) has been observed at room temperature in GaAs / granular film heterostructures in the avalanche state, where a granular film contains ferromagnetic metal nanoparticles or ferromagnetic islands on the semiconductor / film interface. The value of this effect is two-three orders higher than the maximum values of the giant magnetoresistance in the metal magnetic multilayers and the tunnelling magnetoresistance in the magnetic tunnel junction structures. Magnetoresistance effects of high values have been found in GaAs / granular film heterostructures with granular films containing ferromagnetic metal MnSb nano-islands [3, 4] and ferromagnetic MnAs clusters [5]. The high values of the magnetoresistance based on the avalanche breakdown has been observed on the $\text{SiO}_2(\text{Co})/\text{GaAs}$ heterostructures, where the $\text{SiO}_2(\text{Co})$ is the granular SiO_2 film containing Co nanoparticles [6, 7, 8, 9]. This effect has been called the injection magnetoresistance (IMR). It appears, when electrons are injected from the granular film into the GaAs.

Field-effect HEMT devices with spin polarized electron channels are perspective due to the possibility to change electron spins in channels by a magnetic field action. In this paper, we study devices on the base of magnetic nanostructures with silicon dioxide films with cobalt

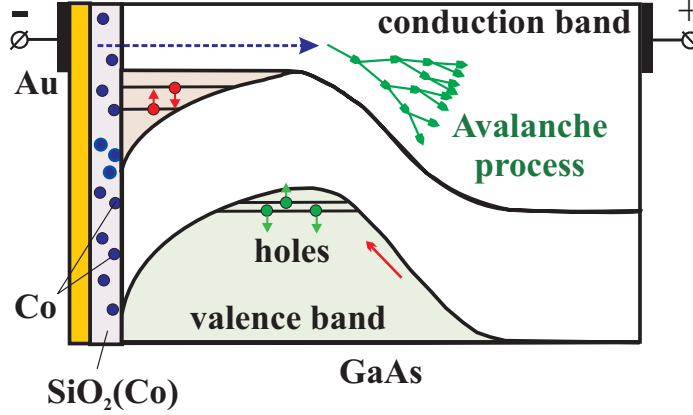


Figure 1: Schematic energy band diagram of the magnetoresistive sensor on the base of the heterostructure with a quantum well near the interface and a hole trap in the avalanche regime.

nanoparticles $\text{SiO}_2(\text{Co})$ on GaAs substrate – magnetic sensors and field-effect transistor governed by applied magnetic field. Magnetic sensors are based on the IMR effect. The field-effect transistor contains the $\text{SiO}_2(\text{Co})$ film under gate. The magnetic field action leads to great changes in the electron mobility in the channel due to the interaction between spins of Co nanoparticles and electron spins.

2 Giant injection magnetoresistance and magnetic sensors

High values of the IMR-effect in the $\text{SiO}_2(\text{Co})$ heterostructures are explained by the magnetic-field-controlled process of impact ionization in the vicinity of the spin-dependent potential barrier formed in the semiconductor (Fig. 1). The spin-dependent potential barrier is formed near the interface by the exchange interaction between the electrons in localized states in the electron accumulation layer in the semiconductor and d -electrons of Co [8, 10]. The avalanche process is induced by electrons, which (1) surmount over the spin-dependent potential barrier formed by the exchange-splitted localized states and (2) tunnel from the localized states. The impact ionization induced by the injected electrons produces holes, which move, are accumulated in the region of the potential barrier and lower the barrier height [8]. Owing to the formed hole feedback, small variations in the barrier height lead to great changes in the current and in the avalanche process. The applied magnetic field increases the barrier height, reduces the transparency of the barrier, and suppresses the onset of the impact ionization.

Magnetic sensors were performed on the samples $\text{SiO}_2(\text{Co})/\text{GaAs}$ with the n -GaAs substrates. Carrier concentrations in the n -GaAs are equal to 10^{15} cm^{-3} . The $\text{SiO}_2(\text{Co})$ films were deposited by the ion-beam co-sputtering of the composite cobalt-quartz target onto the GaAs substrates heated to 200°C . The concentration of Co nanoparticles in the silicon dioxide was varied by changing the ratio of target areas of cobalt and quartz areas. The film composition was determined by the nuclear physical methods of element analysis using a deuteron beam of the electrostatic accelerator (Rutherford backscattering spectrometry and nuclear reaction with oxygen). For the samples used in magnetic sensors, the relative Co content is in the range

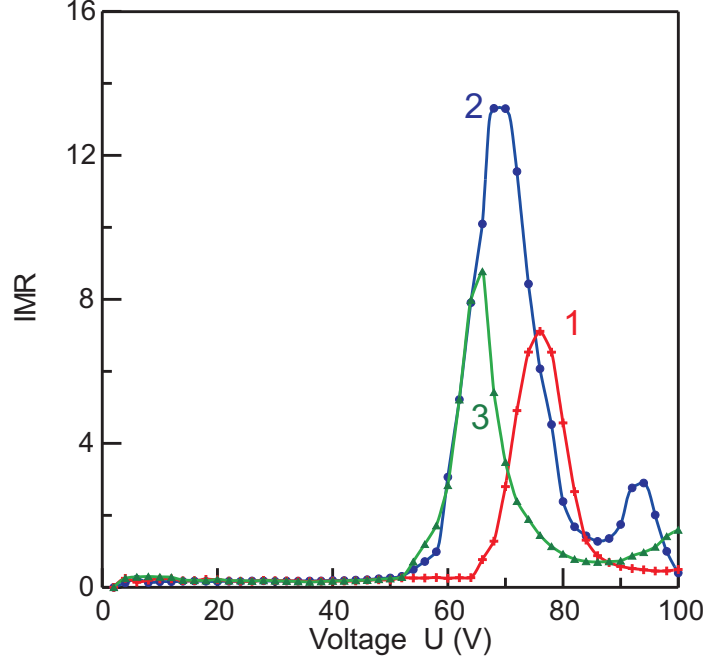


Figure 2: Injection magnetoresistance ratio, IMR, of magnetic sensors versus the applied voltage U in the magnetic field $H = 2.1$ kOe for $\text{SiO}_2(\text{Co})/\text{GaAs}$ heterostructures with Co concentrations (1) - 54 at.%, (2) - 60 at.%, (3) - 71 at.%.

45 - 71 at.% and the film thickness is 40 nm. The average size of Co particles, determined from the low-angle X-ray scattering measurements, increases with Co content: from 2.9 nm at 45 at.% to 3.9 nm at 71 at.%. As the Co content increases, the resistivity of the $\text{SiO}_2(\text{Co})$ films decreases from $0.3 \Omega\cdot\text{cm}$ (45 at.%) through $3.0\cdot 10^{-3} \Omega\cdot\text{cm}$ (60 at.%) to $1.4\cdot 10^{-3} \Omega\cdot\text{cm}$ (71 at.%). The protective Au layer of the thickness 3 - 5 nm have been sputtered on the $\text{SiO}_2(\text{Co})$ films.

The sizes of the samples in magnetic sensors were equal to $3 \times 3 \times 0.4$ mm. One contact was on the GaAs substrate, and the other – on the Au layer sputtered on the granular film. Magnetic sensors are characterized by the injection magnetoresistance, which is defined by the coefficient

$$IMR = \frac{R(H) - R(0)}{R(0)} = \frac{j(0) - j(H)}{j(H)},$$

where $R(0)$ and $R(H)$ are the resistances of the $\text{SiO}_2(\text{Co})/\text{GaAs}$ heterostructure without a field and in the magnetic field H , respectively; $j(0)$ and $j(H)$ are the current densities flowing in the heterostructure in the absence of a magnetic field and in the field H . The IMR ratio for $\text{SiO}_2(\text{Co})/\text{GaAs}$ heterostructures with different Co concentrations versus the applied voltage U in the magnetic field $H = 2.1$ kOe at room temperature is shown in Fig. 2. The magnetic field H is parallel to the film. According to [8], for magnetic fields of high values (> 10 kOe) the IMR coefficient increases with the growth of the applied voltage. In contrast to this, for low magnetic fields the IMR reaches highest values in the region of the avalanche onset. As one can see from Fig. 2, in order to reach high sensitivity of sensors it is need to apply the voltage in this region.

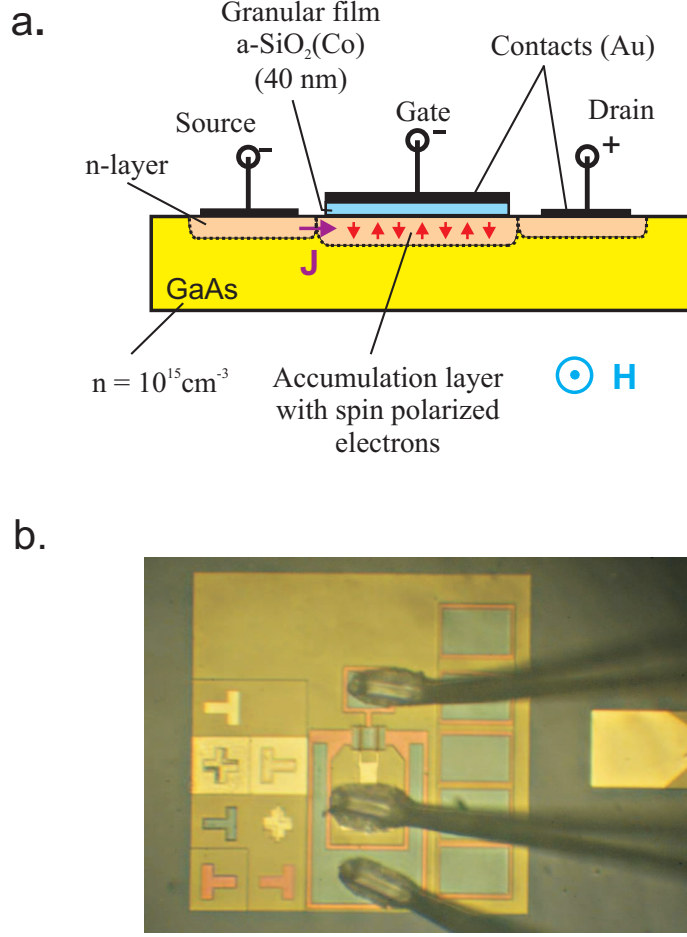


Figure 3: Field-effect HEMT device with spin polarized electron channel under gate electrode. (a) Schematic structure, (b) topology of contacts.

3 Field-effect transistor governed by magnetic field

The field-effect HEMT device with a spin polarized electron channel was developed on the base of the n -GaAs/AlGaAs heterostructures (Fig. 3). This device contains an amorphous granular $\text{SiO}_2(\text{Co})$ film with cobalt nanoparticles under the gate electrode. The thickness of the film is equal to 40 nm. The $\text{SiO}_2(\text{Co})$ film polarizes electron spins in the accumulation layer under the gate.

Current-voltage curves of field-effect devices have two different parts [11]. If the voltage between the source and the drain U_{sd} is less than the saturation voltage $U_{sd}^{(sat)}$, then the current-voltage curve is sub-linear and the current J flowing in the channel is written as

$$J = \frac{\mu C b}{l} \left[(U_{gs} - U_{gs}^{(thr)}) U_{sd} - \frac{1}{2} U_{sd}^2 \right], \quad (1)$$

where U_{gs} is the voltage between the gate and the source, $U_{gs}^{(thr)}$ is the threshold voltage between the gate and the source, when there is no current in the channel, C is the specific capacity between the gate and the channel, μ is the electron mobility, b and l are the channel width and the length, respectively. When $U_{sd} = U_{sd}^{(sat)}$, the channel becomes blocked at the drain contact

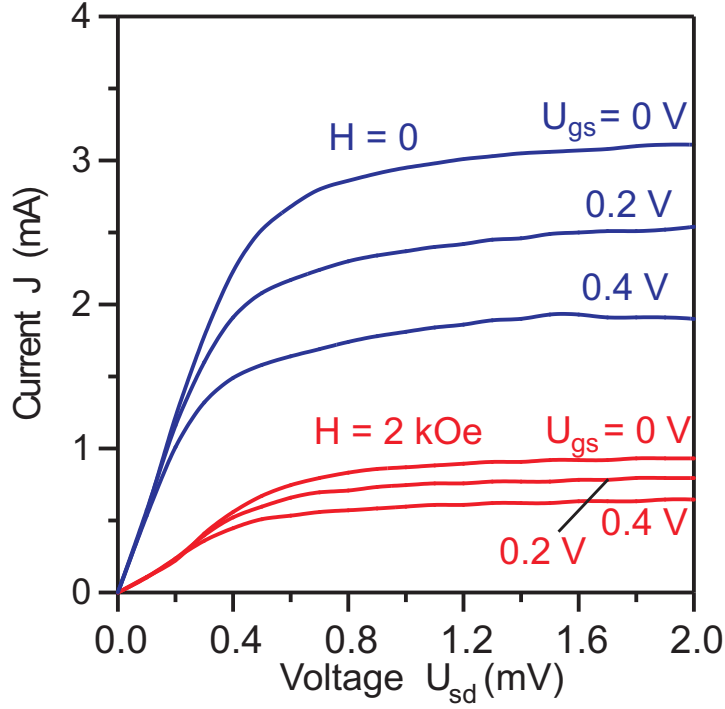


Figure 4: Current-voltage dependences of the field-effect HEMT device in the magnetic field $H = 2$ kOe and without a magnetic field. U_{sd} is the drain voltage, U_{gs} is the voltage at the gate electrode.

and an electrical field of high value appears in this region. In this case, the saturation voltage is

$$U_{sd}^{(sat)} = U_{gs} - U_{gs}^{(thr)}.$$

For $U_{sd} \geq U_{sd}^{(sat)}$ the drain current J is weakly dependent on the voltage U_{sd} and the current-voltage curve can be approximated by a line with a weak slope. In the first approximation this sloping part of the current-voltage curve can be written as

$$J = \frac{\mu C b}{2l} (U_{gs} - U_{gs}^{(thr)})^2, \quad (2)$$

The current-voltage dependences of the developed field-effect HEMT structure (Fig. 4) contain two parts of the current-voltage curve described by relations (1) and (2). The saturation voltage $U_{sd}^{(sat)}$ is in the range 0.4 - 0.7 mV. As one can see from Fig. 4, the drain current J of the field-effect transistor presents strong dependence on the governed external magnetic field H . The electron mobility μ in the channel decreases with the growth of the applied magnetic field. This property can be used in magneto-sensitive devices.

4 Conclusions

We study devices on the base of magnetic nanostructures containing silicon dioxide films with cobalt nanoparticles $\text{SiO}_2(\text{Co})$ on GaAs substrate – magnetic sensors and field-effect transistor.

Magnetic sensors are based on the injection magnetoresistance effect in the avalanche onset regime. The field-effect transistor contains $\text{SiO}_2(\text{Co})$ film under gate. The both structures exhibit high magnetic sensitivity at room temperature.

Acknowledgments

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